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ADVANCE CONFIDENTIAL REPORT #220

A BRIEF STUDY OF THE SPEED REDUCTION OF OVERTAKING AIRPLANES BY MEANS OF AIR BRAKES

By H. A. Pearson and R. F. Anderson
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SUMMARY

As an aid to airplane designers interested in providing pursuit airplanes with decelerating devices intended to increase the firing time when overtaking another airplane, formulas are given relating the pertinent distances and speeds in horizontal flight to the drag increase required.

Charts are given for a representative parasite-drag coefficient from which the drag increase, the time gained, and the closing distance may be found. The charts are made up for three values of the ratio of the final speed of the pursuing airplane to the speed of the pursued airplane and for several values of the ratio of the speed of the pursued airplane to the initial speed of the pursuing airplane. Charts are also given indicating the drag increases obtainable with double split flaps and with conventional propellers. The use of the charts is illustrated by an example in which it is indicated that either double split flaps or, under certain ideal conditions, reversible propellers should provide the speed reductions required.

INTRODUCTION

Experiences of fighter pilots in the current war have indicated that there are numerous occasions where a decelerating device could be used to advantage. One of these occasions occurs when a fighter overtakes a bomber at night. By the time contact is definitely established the bomber is usually being approached so rapidly that there is insufficient time for accurate firing before it is necessary to swerve in order to avoid a collision.

The necessary deceleration obviously can be obtained by an increase in the drag, by a decrease in the thrust, or by combinations of both. Regardless of which method is used, it is desirable in the slowing-down process that there should be no sudden additional forces nor moments introduced which would cause the pilot to lose his line of fire.

As a preliminary criterion Dr. Edward Warner, who had talked with fighter pilots in England, suggested the following as requirements for a decelerating device: ". . . an average acceleration of one third gravity over a speed range from 300 to 150 miles per hour should be taken as the ideal, and it should be possible to secure the full effect within two seconds of the first application of the control or to take the brake off within a similar time."

Ideas of others on this subject have been that, for day fighters, the device should be capable of slowing from 400 to 300 miles per hour and, for night fighters, from 300 to 200 miles per hour with average decelerations of 1 g and 1/2 g, respectively. Such criterions are relatively incomplete as they contain neither the initial distances involved nor the time during which the deceleration is to act. The fact that the initial distances will vary with pilots and that the overtaking velocities will vary according to the airplanes involved further serves to complicate the establishment of fixed criterions and indicates that a somewhat more detailed study would be desirable.

The present brief bulletin includes such a study and indicates, for a particular type of deceleration, the relations between initial distances, necessary drag, and firing time gained for various combinations of airspeed of a fighter and of a bomber. The possibilities of the double split flap and the reversible-pitch propeller as decelerating devices are considered.

In the type of deceleration considered, the braking device is assumed to be moved instantly to a fixed position so that the deceleration decreases with time. Another possibility would be to assume a constant deceleration, in which case the main problem becomes the determination of the motion of the braking device, inasmuch as the time gained and the velocity reduction can be obtained directly.

EQUATIONS

The relation between the force required to decelerate one aircraft overtaking another and the speeds, times, and distances are outlined, the notation of figure 1 being used. In figure 1, the airplanes are in horizontal flight and the distances traveled are referred to the ground, starting with the position of the pursuing airplane when the drag-increasing device is first operated. In night fighting this position might be at the instant that the bomber is first sighted or in day fighting when the bomber first came into extreme range. At this instant let the speed of the fighter be V_o and the horizontal distance between the two airplanes be l_1. Let nV_1 be the speed of the fighter at the distance l_e at which firing contact is broken. Thus l_e might be considered as the distance at which the fighter airplane would be in effective range of the guns of the bomber or the distance at which it is necessary to swerve in order to avoid collision. Assume that the speed of the bomber is maintained at a constant value V_1 during the time interval t that the fighter closes from l_1 to l_e. In this interval the bomber travels the distance

$$X_1 = V_1 t$$

and the fighter travels the distance

$$X = \int_0^t V\,dt$$

thus

$$l_1 - l_e = \int_0^t V\,dt - V_1 t \qquad (1)$$

For the fighter the speed changes during the interval that the device is in operation according to the equation

$$\frac{dV}{dt} = \frac{T - C_D \frac{\rho}{2} V^2 S}{\frac{W}{g}} \qquad (2)$$

where the symbols have their usual significance. The induced drag increases during the slowing-down process because the airplane, in order to maintain level flight, must increase its angle of attack unless the lift is also increased as the speed is decreased. If constant engine speed and constant pitch setting is maintained, the thrust will, in general, also increase. Since these two effects tend to counteract each other, it seems reasonable, at this stage, to make the assumption that the thrust remains constant and equal to its initial value of

$$T = C_{D_o} \frac{\rho}{2} V_o^2 S \tag{3}$$

and that the drag coefficient is equal to

$$C_D = C_{D_o} + \Delta C_D \tag{4}$$

where

C_{D_o} initial drag coefficient

ΔC_D increase in drag coefficient introduced by operating a drag-increasing device, such as double split flaps. (It is assumed here that ΔC_D remains constant during the speed change.)

The effect of reversing the propeller blade angle will be considered later. Substituting equations (3) and (4) into equation (2) gives

$$dt = \frac{WdV}{g\frac{\rho}{2}S\left[C_{D_o}V_o^2 - \left(C_{D_o} + \Delta C_D\right)V^2\right]} \tag{5}$$

from which

$$\int_o^t Vdt = \frac{W}{g\frac{\rho}{2}S} \int_{V_o}^{nV_1} \frac{VdV}{C_{D_o}V_o^2 - \left(C_{D_o} + \Delta C_D\right)V^2} \tag{6}$$

Integrating equation (6) and inserting the limits gives

$$\int_0^t V dt = -\frac{W}{g\rho S}\left(\frac{1}{C_{D_o} + \Delta C_D}\right) \log_e \left[\frac{(nV_1)^2 - \dfrac{C_{D_o} V_o^2}{C_{D_o} + \Delta C_D}}{V_o^2 - \dfrac{C_{D_o} V_o^2}{C_{D_o} + \Delta C_D}}\right] \tag{7}$$

If equation (5) is integrated between the limits V_o and nV_1 and the resulting equation simplified, there is obtained for the time elapsed

$$t = \frac{W}{g\rho S}\left[\frac{1}{V_o\sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}\right]\log_e \left[\frac{\dfrac{C_{D_o}V_o + nV_1\sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}{C_{D_o}V_o - nV_1\sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}}{\dfrac{C_{D_o} + \sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}{C_{D_o} - \sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}}\right] \tag{8}$$

By substitution of equations (7) and (8) into equation (1) there are then obtained the relations between the drag increase, the closing distances, and the overtaking velocities given by

$$l_1 - l_e = -\frac{W}{g\rho S}\left\{\frac{1}{C_{D_o} + \Delta C_D} \log_e \left[\frac{(nV_1)^2 - \dfrac{C_{D_o} V_o^2}{C_{D_o} + \Delta C_D}}{V_o^2 - \dfrac{C_{D_o} V_o^2}{C_{D_o} + \Delta C_D}}\right]\right.$$

$$\left. + \frac{V_1}{V_o\sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}\log_e \left[\frac{\dfrac{C_{D_o}V_o + nV_1\sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}{C_{D_o}V_o - nV_1\sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}}{\dfrac{C_{D_o} + \sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}{C_{D_o} - \sqrt{C_{D_o}(C_{D_o} + \Delta C_D)}}}\right]\right\} \tag{9}$$

Equation (9) may be expressed in the form of a dimensionless distance traveled by the fighter airplane with respect to the bomber by dividing by $\frac{W}{g\rho S}$.

The additional firing time gained by the use of an instantaneous speed-reducing device over the firing time without a speed-reducing device is equal to

$$t_{gained} = t - \frac{l_1 - l_e}{V_o - V_1} \tag{10}$$

CHARTS FOR DETERMINING DRAG REQUIRED

In order to provide a basis for calculating the drag increase necessary to obtain a given speed change, values have been computed from equations (8) and (9) for $C_{D_o} = 0.02$, three values of n (factor by which the final speed of the fighter is greater than that of the bomber), and several values of V_1/V_o. The results are given in the form of curves of ΔC_D plotted against the dimensionless closing distance $\frac{(l - l_e)g\rho}{\frac{W}{S}}$ on figures 2, 3, and 4. The results are thus applicable to any wing loading and air density (altitude). Values of a dimensionless time $\frac{tV_o g\rho}{\frac{W}{S}}$ have been cross-plotted on the figures to facilitate the calculation of t.

As an illustration of the use of the charts, consider the case where it is required to find the instantaneous drag-coefficient increase that would be necessary under the following conditions:

Indicated airspeed of bomber on course V_1, miles per hour	150
True airspeed of bomber on course V_1, feet per second	239.5
Initial indicated airspeed of overtaking fighter V_o, miles per hour	300

True airspeed of overtaking fighter V_o, feet per second 479
Initial distance from bomber when the drag-increasing device is first operated l_1, feet . 1000
Distance from bomber at which contact is to be broken l_e, feet 50
W/S, pounds per square foot 36
Mass density of air ρ, (altitude 5800 ft) 0.002
Final speed of fighter equals speed of bomber (n = 1)

From these values,

$$\frac{(l_1 - l_e)g\rho}{\frac{W}{S}} = 1.70$$

Reference to figure 2(for $n = 1$) and to the curve labeled $V_1/V_o = 0.5$ shows that the required increase in drag coefficient is equal to 0.245 and $\frac{tV_o g\rho}{\frac{W}{S}} = 9.3$.

Then

$$t = \frac{9.3 \times 36}{479 \times 32.2 \times 0.002} = 10.9 \text{ sec}$$

If there were no checking of the fighter speed, the time to close 950 feet would be

$$\frac{1000 - 50}{479 - 239.5} = 4.0 \text{ sec}$$

so that the additional firing time gained is

$$10.9 - 4.0 = 6.9 \text{ sec}$$

Thus, in this instance, the firing time is nearly trebled and additional firing time would be gained as the bomber drew away. The increase in angle of attack would be about 6° (for a lift-curve slope of 0.075, in deg units). As will be mentioned later, it may therefore be desirable to prevent a change in attitude by maintaining constant lift. A method such as the additional opening of a lower flap could be used.

The drag coefficient increase of 0.245, specified by the conditions of the problem, can be obtained, as was previously pointed out, by the use of a single device or can be made up of increments due to each of several devices, such as double split flaps, split rudders, reversible propeller, and so forth.

It is realized that the speed of a bomber will probably not remain constant when it is attacked, but the drag coefficients found from the figures will at least give an approximation to the value required.

DOUBLE SPLIT FLAP

The drag of wings with double split flaps should be obtained by tests or by calculation, an integration across the span and appropriate section-drag coefficients being used. As there are, however, few data available, the following method is given to aid in finding the order of magnitude of the drag increase obtainable.

Figure 5 shows the variation with flap-chord ratio of the increment of section-drag coefficient due to deflecting (nonperforated) double split flaps equally and oppositely. The curves given are based on the assumption that the drag increase of the combination is equal to the ratio of the projected flap area to the wing area multiplied by the drag coefficient (1.25) of a flat plate normal to the wing. This assumption yields the following equation for the increment of section drag coefficient Δc_{d_o}:

$$\Delta c_{d_o} = 2.50\ KE \sin \delta \qquad (11)$$

where

E flap-chord ratio, c_f/c

δ flap deflection

K empirical factor

The empirical factor was obtained by inserting experimental values of Δc_{d_o}, taken from unpublished test results of a 0.2 chord double split flap, into equation

(11) and solving for K. The airfoil was 12 percent thick and the test Reynolds number was 600,000.

The data of figure 5 represent the limiting case of nonperforated flaps. Flight tests have indicated that flaps are usually preferable, but if it is desired to use perforated flaps the values of figure 5 should be reduced somewhat. Although data showing the effect of perforations are meager at present, the results of reference 1 indicate that 85 percent of the solid flap drag was realized with 33.1 percent of the area removed by the perforations.

The results given in figure 5 are applicable without modification to the case of full-span double split flaps of constant chord ratio $(\Delta C_D = \Delta c_{d_o})$. It is seen that the drag-coefficient increase sought, that is, 0.245, could be easily obtained with flaps of relatively small chord extending across the span. If it were desirable, however, to obtain the desired increase with partial-span flaps, the values given in figure 5 would have to be increased in the ratio of the total wing area S to the wing area in front of the flaps S' $\left(\Delta C_D = \frac{S}{S'} \Delta c_{d_o}\right)$. The increase factor S/S' is shown in figure 6 plotted against flap span for various wing taper ratios for wings with trapezoidal tips.

In order to illustrate the use of figure 6, assume that the necessary increase in ΔC_D is to be obtained by the use of a half-span double split flap on a 2:1 tapered wing, that is, ratio of tip chord to root chord $\lambda = 0.5$. Referring to figure 6 the increase factor for $b_f/b = 0.5$ is found to be 1.72, so that, the Δc_{d_o} required is $1.72 \times 0.245 = 0.422$. Reference to figure 5 indicates that this increase would be obtained with the following combinations of E and δ:

E	δ (deg)
0.176	90
.193	75
.230	60
.306	45

It can be seen that a double split flap can easily be selected which could meet even more severe conditions than those chosen. Even though such capabilities exist with the double split flap it is questionable whether they could be fully utilized because of the increased deceleration that would occur with larger flaps and larger deflections. Pilots evidently feel that an average deceleration of 1 g is a maximum which can be allowed if accuracy in firing is to be had. For the example given the initial deceleration when the flaps are first deflected is

$$a = \frac{\Delta C_D q_o g}{\frac{W}{S}} = \frac{0.245 \times 229g}{36} = 1.56g$$

and the deceleration when the fighter breaks contact at a speed of 150 miles per hour is 0.39g. From a curve of deceleration plotted against time, the average deceleration was found to be 0.78g, and a straight average yields a value of 0.98g.

Results of a step-by-step computation (reference 2) for an airplane using the split flaps as a brake, indicates that by an additional progressive angle increase of the lower flap a practically constant attitude may be maintained. Thus, the charts given in this paper may be used to determine average flap conditions and further calculations may be made if it is considered desirable to increase the angle of the lower flap.

REVERSIBLE PROPELLERS

Although some braking can be obtained simply by throttling the engine, this amount of braking, in the light of the criterions which have already been advanced, would be inadequate. In order to obtain the required amount of braking from a conventional propeller it would be necessary not only to be able to abruptly reduce the pitch setting but also to supply power from the engine. The following analysis will indicate roughly the drag increases which could be expected from a conventional propeller under rather ideal conditions.

If the thrust of a propeller is expressed by the equation

$$T = C_T \rho n^2 D^4$$

and it is assumed that the propeller is instantly reversed from its normal operating position β_1 to another position β_2 at the same V/nD the change in thrust or drag increase would be given by

$$\Delta T = C_{T_2} \rho\ n^2 D^4 - C_{T_1} \rho\ n^2 D^4 \tag{12}$$

To convert this change in thrust to an increment in drag coefficient based on the wing area, let ΔT be given by

$$\Delta T = \Delta C_D \frac{\rho}{2} V^2 S \tag{13}$$

Then

$$\Delta C_D = \frac{8}{\pi} \frac{S_D}{S} \left(C_{T_2} - C_{T_1}\right) \left(\frac{nD}{V}\right)^2 \tag{14}$$

where S_D is the propeller disk area.

In general the values of C_{T_1} and C_{T_2} will depend on several variables, such as number of blades, solidity, initial and final blade setting, and V/nD. For purposes of making quantitative comparisons of the drag-increasing capabilities of the propeller with those of the double split flap, results from some unpublished data have been evaluated to give the curves shown in figures 7 and 8. Figure 7(a) gives the value of $C_{T_2} - C_{T_1}$ for various blade-angle reductions for each of a number of initial blade-angle settings. The data given was obtained on a two-blade Clark Y propeller of 10-foot diameter tested at relatively low tip speeds. In the derivation of figure 7 it was assumed that at cruising speed, the propeller would be initially operating at the C_T corresponding to the V/nD of maximum efficiency, which would also automatically determine the initial values of the power or torque coefficients C_P and C_Q defined by

$$C_P = \frac{\text{engine power}}{\rho\ n^3\ D^5} \qquad C_Q = \frac{Q}{\rho\ n^2\ D^5}$$

If the pitch were then abruptly reduced, with the V/nD remaining the same, new values of C_T and C_Q could be obtained for initial blade settings as high as 65° to final blade settings as low as -25°. Whereas figure 7(a) shows that a reduction in thrust is always obtained regardless of the initial setting and the amount of the blade-angle reduction, figure 7(b) shows that if the reduction in blade angle is not sufficient, a windmilling torque will be exerted on the propeller, tending to overspeed the engine unless the throttle setting is also reduced. At the value of $\Delta\beta$ where $C_{Q_2} - C_{Q_1} = 0$ there would be no overspeeding, but if the change in blade angle is greater than this amount, it would be necessary to supply additional power. Since the maximum values of $C_{T_2} - C_{T_1}$ for a given initial blade setting will occur beyond the value where $C_{Q_2} - C_{Q_1} = 0$, it would, in most cases, be necessary to supply power to obtain a maximum of braking from the propeller.

Figure 8 shows the increase in airplane drag coefficient that is obtainable with the propeller. The curves given are derived by substituting the values from figure 7(a) into equation (14), assuming a value of $\frac{S_D}{S} = 0.318$, and assigning to V/nD the value holding at maximum efficiency for the various initial blade settings. The curves on this figure show that the drag-coefficient increment decreases as the initial blade setting increases. It is also indicated that the maximum value of ΔC_D occurs at a $\Delta\beta$ of about 60°.

Comparison of these values of ΔC_D with those obtainable with a double split flap indicates that the conventional propeller does not have ultimate capabilities as great as the flap for reducing the speed. In the present instance, however, it will be noticed that the ΔC_D of 0.245 required in the previous example could theoretically be obtained with the propeller if the characteris-

tics of the airplane were such that the initial blade setting was no greater than about 30° (fig. 8). In order that there should be no tendency of the engine to change speed the initial blade setting should have been 26° (fig. 8, line of no torque change and $\Delta C_D = 0.245$), and the reduction in blade setting should be $37\frac{1}{2}°$.

The use of the propeller as a worth-while air brake, however, would necessitate a rapid change in blade angle, because otherwise the engine would greatly overspeed unless the throttle were simultaneously adjusted. Some rough calculations for a typical engine-propeller combination indicate that if it required only 1 second to make the change in blade angle, approximately 10 rps would be gained at full throttle. On the other hand, if the throttle setting were changed to reduce any tendency to overspeed, a rolling motion would result. Thus, unless counter-rotating (torque-reaction-free) propellers were used it might be necessary to compensate not only for the effect of airspeed on the attitude angle but also possibly for the resulting rolling motion.

An additional consideration is the effect of the deceleration on the engine- and propeller-strength requirements. As the deceleration caused by reversing the pitch will be several times the acceleration used in take-off, the propeller and engine parts may require strength investigation for the increased loads when the pitch is reversed.

CONCLUDING REMARKS

It has been indicated that speed-reducing devices, such as double split flaps or reversible-pitch propellers, should provide a considerable amount of braking and, consequently, a lengthening of the firing time for a fighter airplane overtaking a bomber.

If double split flaps were used, it would be desirable to adjust one of the flaps after the initial deflection in order to maintain a constant attitude.

If reversible-pitch propellers were used, it would be necessary that large changes in blade angle be possible in a short interval of time (of the order of 1/2 sec) to prevent overspeeding at a constant throttle setting.

In order to avoid possible changes in attitude, not only would counter-rotating propellers be desirable to eliminate rolling tendencies but also a lift-increasing device should probably be used to prevent a change in attitude.

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REFERENCES

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2. Purser, Paul E., and Turner, Thomas R.: Wind-Tunnel Investigation of Perforated Split Flaps for Use as Dive Brakes on a Tapered NACA 23012 Airfoil. NACA A.R.R., Nov. 1941.

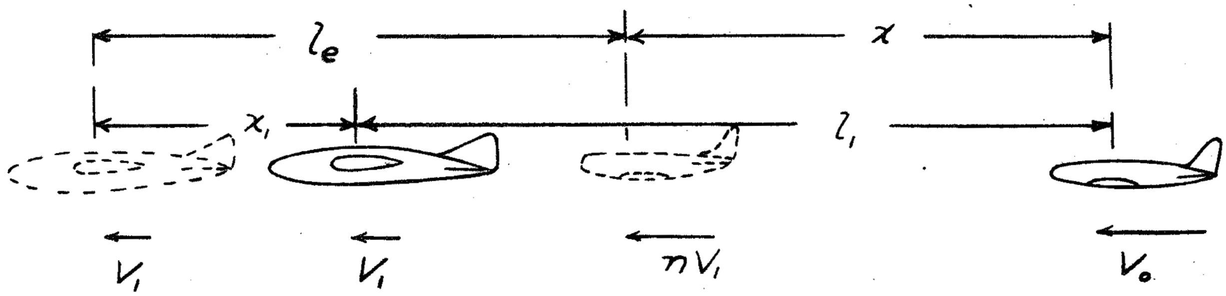

Figure 1.- Conventions used in derivation.

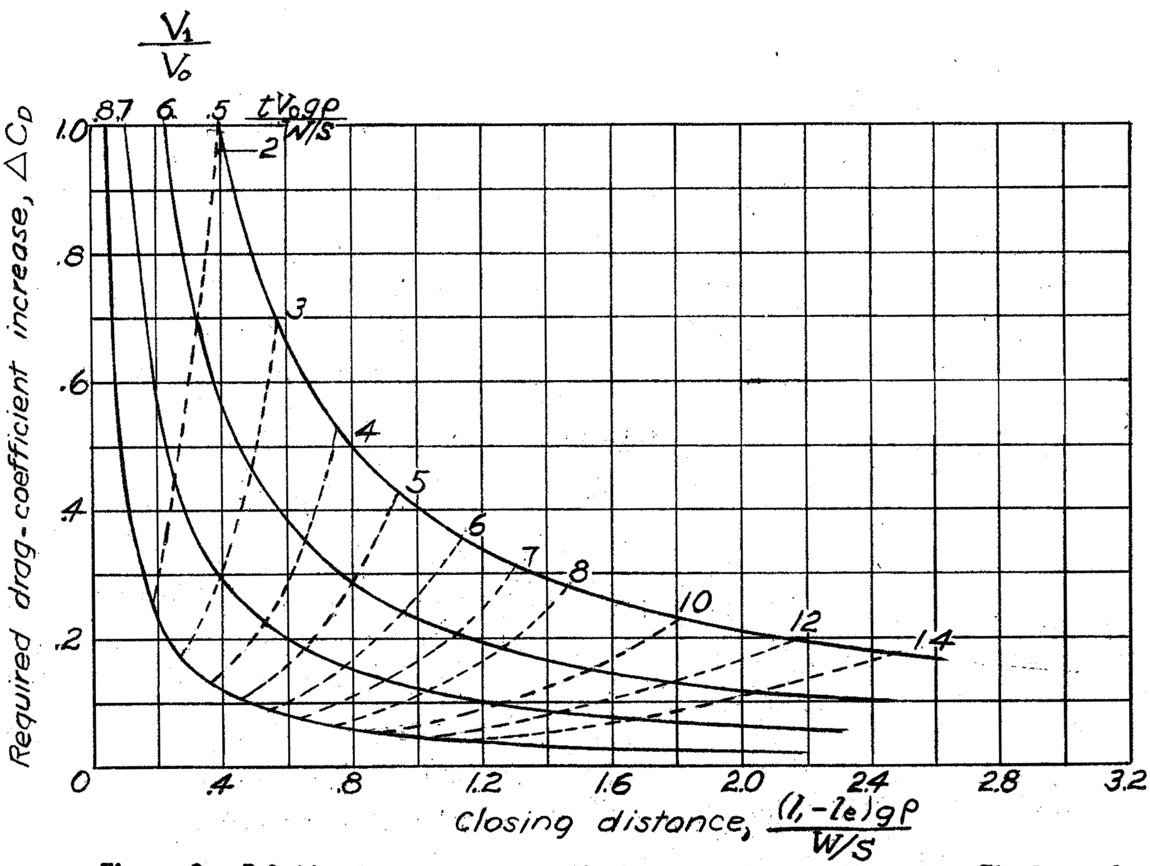

Figure 2.— Relation between drag coefficient and closing distance. Final speed of pursuing airplane equal to speed of pursued airplane.

(n=1)

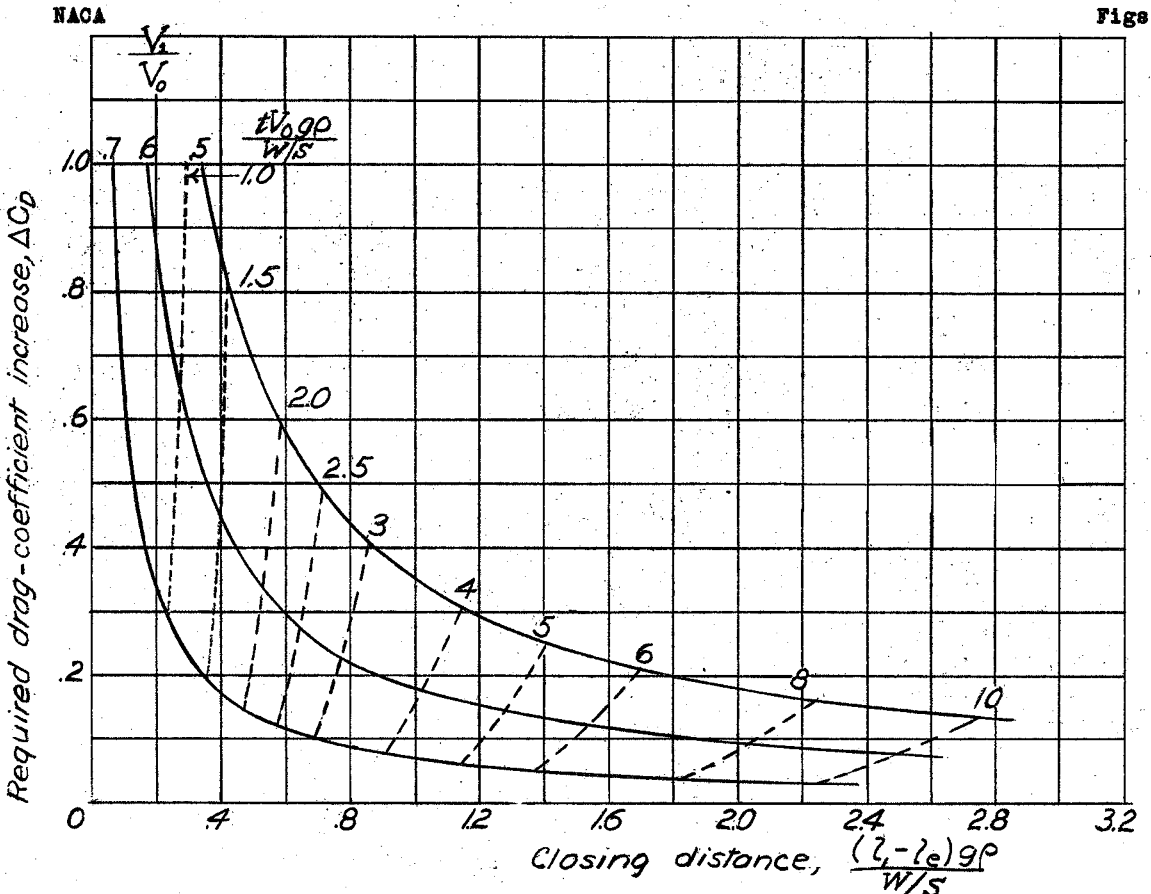

Figure 3.– Relation between drag coefficient and closing distance. Final speed of pursuing airplane equal to 1.25 times the speed of the pursued airplane. (n=1.25)

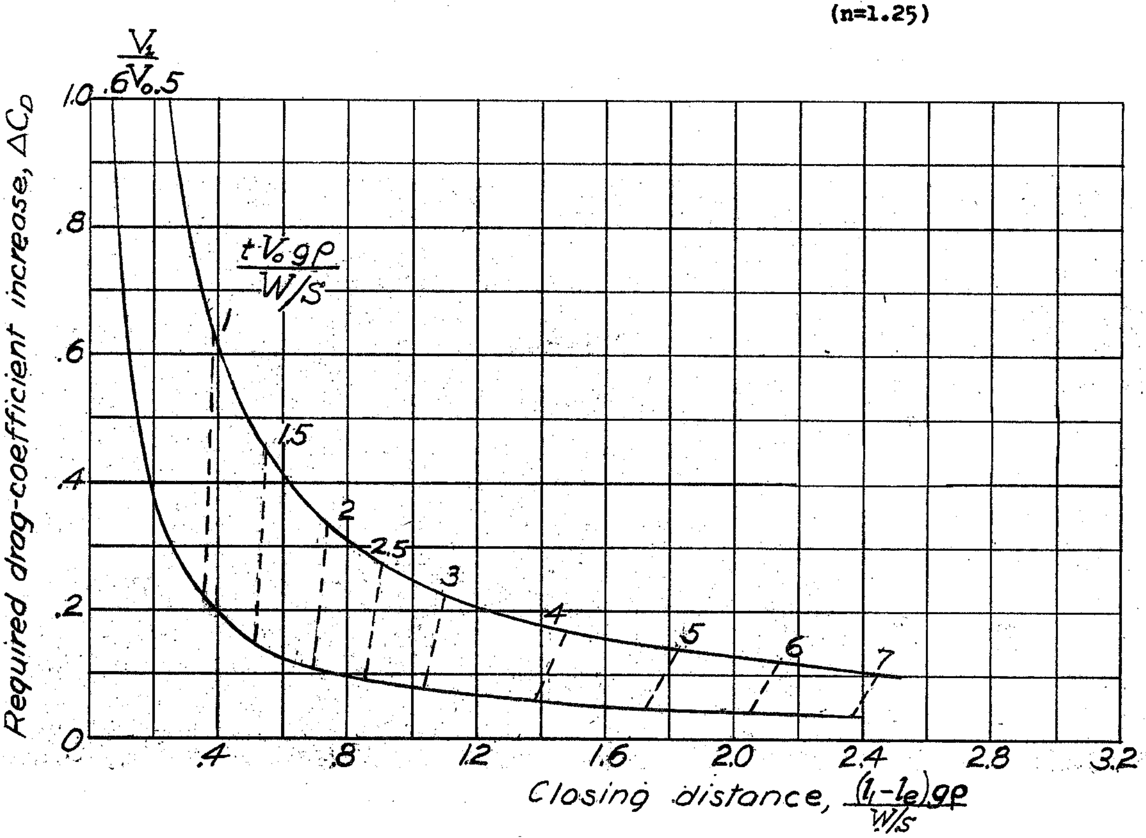

Figure 4.– Relation between drag coefficient and closing distance. Final speed of pursuing airplane equal to 1.5 times the speed of the pursued airplane. (n=1.5)

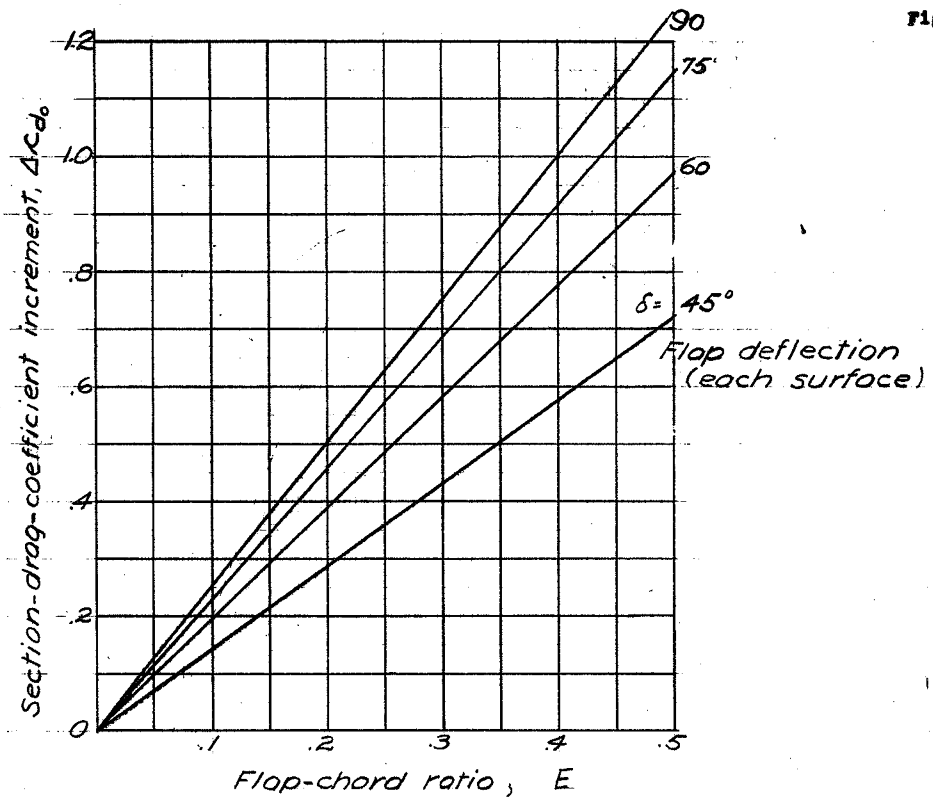

Figure 5.– Estimated drag coefficient increment for nonperforated double split flaps.

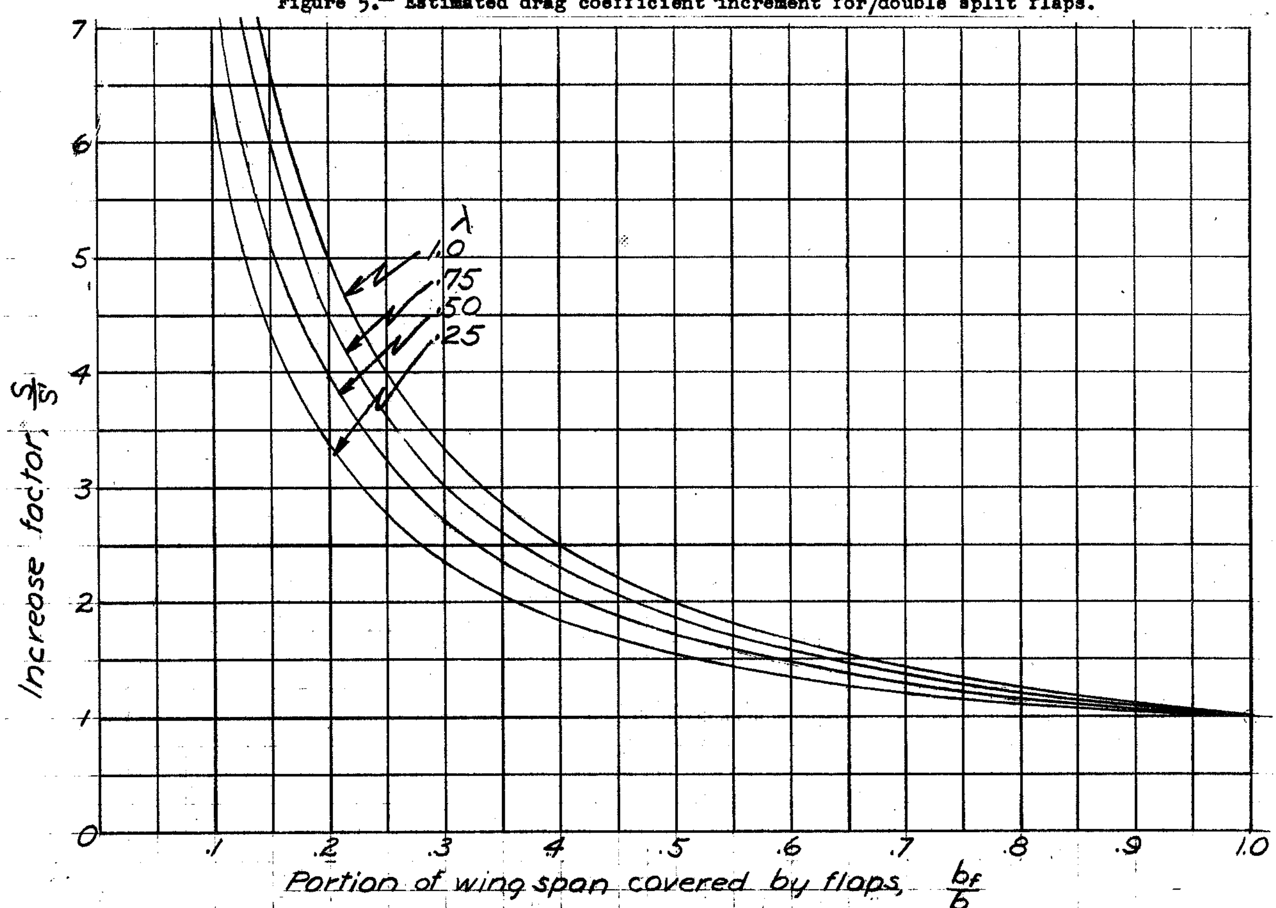

Figure 6.– Increase factor for partial span flaps, for wings with trapezoidal tips.

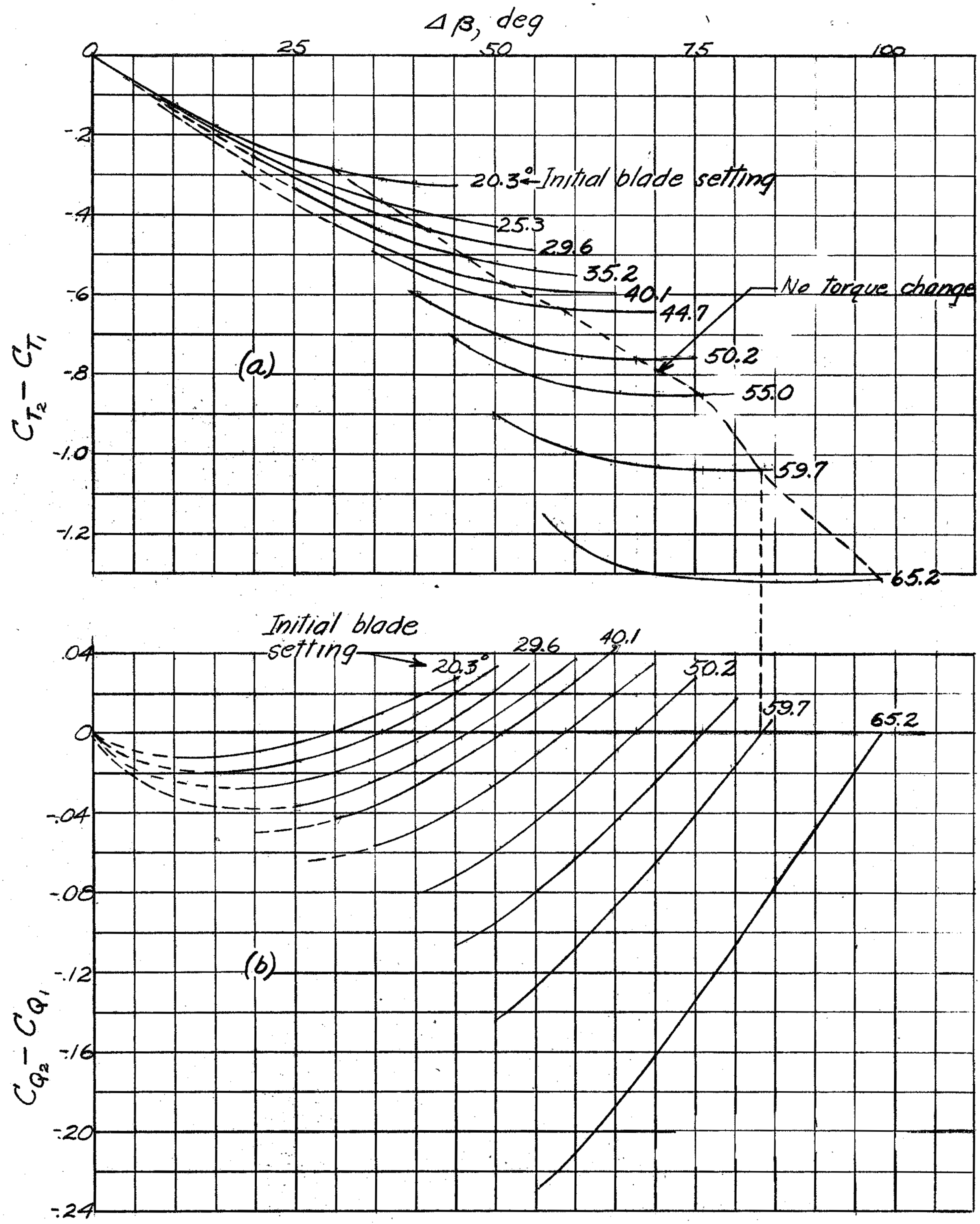

Figure 7.— Change in thrust and torque coefficients caused by suddenly reducing the blade angle.

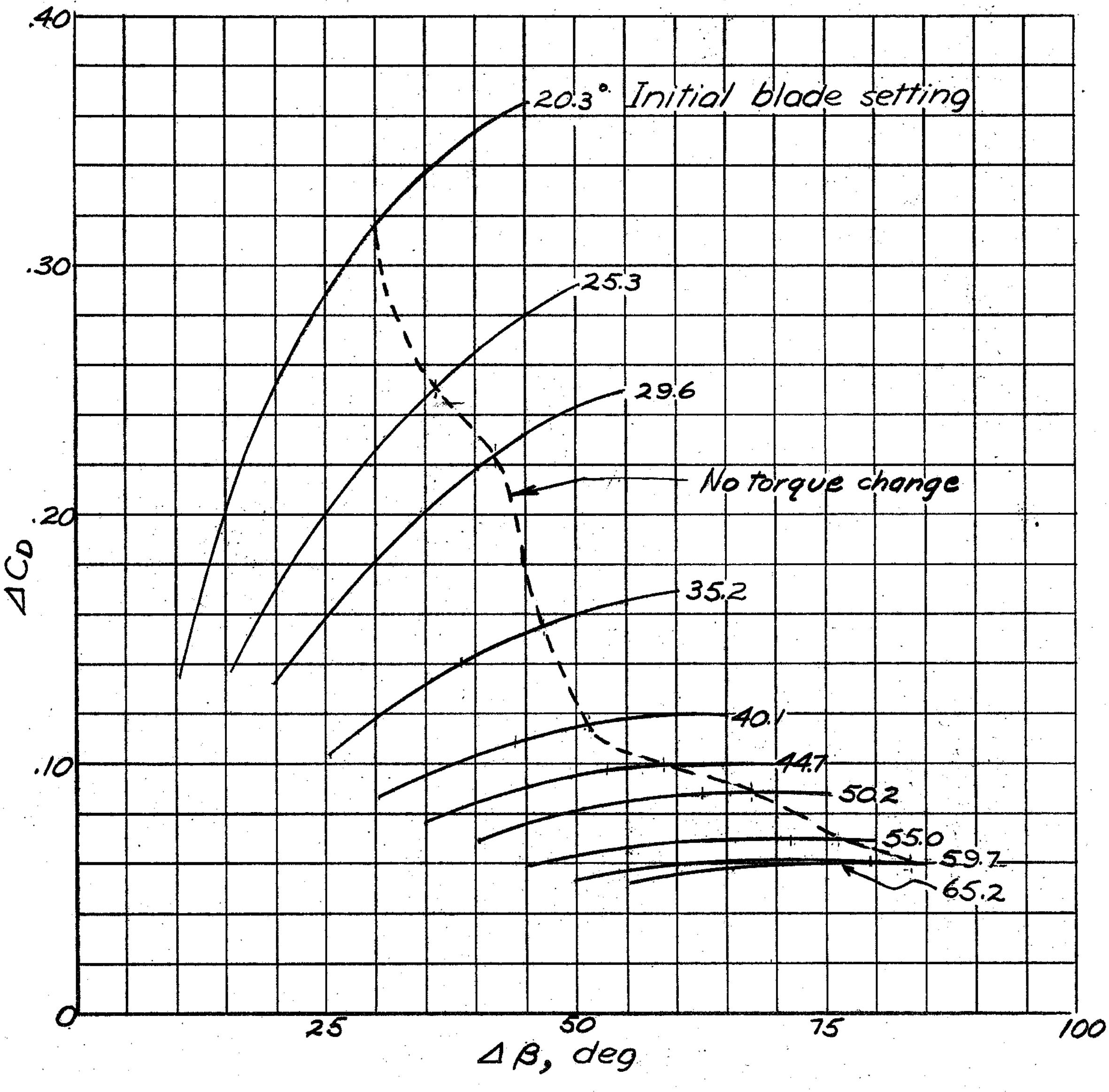

Figure 8.- Change in airplane drag coefficient caused by suddenly reducing the propeller blade angle.